



Simulated Service and Stress Corrosion Cracking Testing for Friction Stir Welded Spun Formed Domes

Thomas J. Stewart*

Pablo D. Torres**

Andrei A. Caratus*

Peter A. Curreri**

*** Jacobs ESTS Group, Huntsville, AL 35806**

**** NASA Marshall Space Flight Center, Huntsville, AL 35812**

Abstract

Simulated service testing (SST) development was required to help qualify a new 2195 aluminum lithium (Al-Li) alloy spin forming dome fabrication process for the National Aeronautics and Space Administration (NASA) Exploration Development Technology Program. The application for the technology is to produce high strength low weight tank components for NASA's next generation launch vehicles. Since plate material is not currently manufactured large enough to fabricate these domes, two plates are joined by means of friction stir welding. The plates are then pre-contour machined to near final thicknesses allowing for a thicker weld land and anticipating the level of stretch induced by the spin forming process. The welded plates are then placed in a spin forming tool and hot stretched using a trace method producing incremental contours. Finally the dome receives a room temperature contour stretch to final dimensions, heat treatment, quenching, and artificial aging to emulate a T-8 condition of temper. Stress corrosion cracking (SCC) tests were also performed by alternate immersion in a sodium chloride (NaCl) solution using the typical double beam assembly and with 4-point loaded specimens and use of bent-beam stress-corrosion test specimens under alternate immersion conditions. In addition, experiments were conducted to determine the threshold stress intensity factor for SCC (K_{ISCC}) which to our knowledge has not been determined previously for Al-Li 2195 alloy. The successful simulated service and stress corrosion testing helped to provide confidence to continue to Ares 1 scale dome fabrication.

Introduction

Simulated service testing development was required to help qualify a new 2195 aluminum lithium alloy (Al-Li) spin forming dome fabrication process for the (NASA) Exploration Development Technology Program. The application for the technology is to produce high strength low weight tank components for NASA's next generation launch vehicles. Since plate material is not currently manufactured large enough to fabricate these domes, two plates are joined by means of friction stir welding. The plates are then pre-contour machined to near final thicknesses allowing for a thicker weld land and anticipating the level of stretch induced by the spin forming process. The welded plates are then placed in a spin forming tool and hot stretched using a trace method producing incremental contours. Finally the dome receives a room temperature contour stretch to final dimensions, heat treatment, quenching, and artificial aging to emulate a T-8 condition of temper.

The simulated service testing performed was based on a standard used for lot acceptance of plate material for the Space Shuttle External Fuel Tank. This testing is performed on a specimen with an induced flaw of elliptical shape generated by electrical discharge machining (EDM) and subsequent fatigue cycling for crack propagation to a predetermined length and depth. The specimen is then loaded in tension at a constant rate of displacement at room temperature until fracture occurs while recording load and strain. An identical specimen with a similar flaw is then proof tested at room temperature to imminent failure based on the critical offset strain achieved by the previous fracture test. If the specimen survives the proof, it is then subjected to cryogenic cycling with loads that are a percentage of the proof load performed at room temperature. If all cryogenic cycles are successful, the specimen is loaded in tension until failure at the final stage of the test. One challenge presented by the testing was the compound curvature of the dome. The testing was developed on a sub-scale dome with a small diameter. This simulated service standard was generated for flat plate, so a method of translating this to a specimen of compound curvature was required. This was accomplished by fabricating a fixture that maintained the curvature of the specimen rigidly with the exception of a small distance in the center of the specimen containing the induced flaw. This in conjunction with placing the center of the specimen in the center of the load train allowed for successful testing with a minimal amount of bending introduced into the system.

Stress corrosion cracking (SCC) tests were also performed per standard ASTM G44 *Practice for Exposure of Metals and Alloys by Alternate Immersion in Neutral 3.5 % Sodium Chloride Solution* (Ref. 1) using the typical double beam assembly and with 4-point loaded specimens per ASTM G 39 *Standard Practice for Preparation and Use of Bent-Beam Stress-Corrosion Test Specimens* (Ref.2) under alternate immersion conditions in a NaCl environment for 90 days.. In addition, experiments were conducted

to determine the threshold stress intensity factor for SCC ($K_{I_{SCC}}$) per ASTM E 1681 *Test Method for Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials* (Ref. 3) of which to our knowledge has not been determined previously for 2195 Al-Li alloy. The successful simulated service and stress corrosion testing helped to provide confidence to continue to Ares 1 scale dome fabrication.

Subscale Dome Simulated Service Testing

NASA MSFC's Mechanical Test Facility performed two simulated service tests on a subscale spun formed dome. The full details of the subscale dome testing program are given in the contract report (Ref. 4). One simulated service test was performed on the friction stir welded portion of the dome and the other was performed on the parent material.

The simulated service test performed on these specimens was originally developed for lot acceptance of 2195 Al-Li plate used in the construction of the Shuttle External Fuel Tanks. The test was used as a baseline to describe the cryogenic fracture properties of the dome as compared to plate material. Since the dome was spun to near finished dome thickness, the specimen was designed to maintain this curvature. A test fixture was fabricated to maintain the curvature during tensile loading with the exception of a small arc length of the plate to minimize the effects of bending. Two specimens each were fabricated from the parent material and from the area containing the friction stir weld.

A flaw was induced in each specimen on the surface facing the inner skin line. One specimen from both areas of the dome was used as a fracture test to determine the proof level of the simulated service test specimen for the corresponding location. The fracture specimens were loaded monotonically at room temperature at a constant displacement rate using a strain measuring device to record strain data. This strain data was not considered for any purpose other than to obtain an offset strain because the curvature of the specimen induced error into the strain measurements as the load increased and the specimen began to straighten. The simulated service specimens were proof tested at room temperature to a percentage of the critical offset strain witnessed in the fracture tests to emulate imminent failure. After proof testing was performed, the simulated service specimens were submerged in liquid nitrogen (-320°F) and subjected to the loading spectrum set forth in the previously mentioned standard. All of the specimens fell slightly below the net section stress requirement allowed for plate material. Both of the simulated service specimens survived the required post-proof simulated service testing in liquid nitrogen (-320°F).

Full Scale Dome Simulated Service Testing

The Mechanical Test Facility also performed a simulated service test on an Ares I scale dome. This full scale dome fabrication process is still in the early stages of development, so the material properties are not optimized. The specimens used for the simulated service testing came from the pole region of the dome. This location received the least amount of stretch in the fabrication process. For this reason, the material thickness was greater than the subscale dome material. The specimens were tested at this final thickness in the same fashion as the subscale dome with a few exceptions. Also, the full scale dome displayed a significant amount of residual stress resulting in the material springing back to a much smaller diameter.

The specimen geometry of the full scale dome specimens was the same as the subscale except for the radii of curvature and the width of the gage section. Full scale specimens of the same width as the subscale were tested and failed in the grip section of the specimen. Therefore, the gage section had to be reduced on the full scale specimens to allow for failure in the gage section. The reasoning for this change in failure mode is likely two fold. The thickness of the full scale specimen is almost two times that of the subscale specimen. Both specimens received the same flaw geometry, so the full scale specimen had much more ligament left through the thickness below the flaw to prevent fracture. Also, the full scale specimen displayed much more ductile behavior likely due to less strain hardening during fabrication. The specimen that was tested met the net section stress requirement set forth in the standard and survived the required cryogenic cycles.

Subscale Stress Corrosion Cracking Testing

Parent material and friction stir weld specimens were machined from the subscale dome for SCC testing. These specimens were loaded to various percentages of the yield strength of the material and subjected to alternate immersion exposure in a NaCl solution. The SCC specimens were tested using the double beam and 4-point bend loading methods.

There were no specimen failures after the duration of exposure. General pitting was observed on the specimen surfaces; however, this is typical for bare 2xxx series aluminum alloys tested in this manner. In summary, these results indicate that the spun formed material is not susceptible to stress corrosion cracking.

Subscale Threshold Stress Intensity Factor for SCC (K_{ISCC}) Testing

Some smooth surfaced materials that appear to be immune to stress corrosion cracking may be highly susceptible to stress corrosion cracking in the presence of a sharp flaw (crack). Environmentally enhanced crack growth is expected to occur in highly stressed regions, such as at the crack tip. Standard SCC tests are pass/fail tests and do not provide information on the effects of the aggressive environment on the evolution of a flaw (crack). Data obtained from the K_{ISCC} crack growth tests enhance the understanding of the kinetics of SCC and also verify the threshold behavior.

Determination of the K_{ISCC} parameter provides the lowest applied K level that shows evidence of subcritical crack growth after reaching the recommended test duration. In addition, the procedure enables the determination of crack growth rate (da/dt vs. crack length plots). The modified bolt-loaded compact tension specimen was used (constant displacement method) with aggressive environments of NaCl spray solution or full immersion in liquid salt solution. Crack growth was monitored using the voltage drop method (as the crack propagates, the electrical resistance of the specimen changes). Initial (bolt) loading was based on a percentage of K_{IC} .

The materials used in this initial study were the subscale spun formed domes manufactured by a different vendor than the previously mentioned subscale domes. Standard 2195-T8 Al-Li plate was also tested for a baseline. Standard pre-cracked specimens were placed in a NaCl spray solution loaded such that the crack tip produced a very high level state of stress from which environment assisted propagation was expected. The spray solution was chosen rather than full immersion in order to simulate the environmental conditions that exist at NASA's Kennedy Space Center during the storage, assembly, prelaunch and launch holding phases. The bolt loading used in the modified bolt-load compact tension specimen tests provided a constant displacement loading.

Two batches of specimens were tested. The tests duration was approximately 450 hrs. Specimens were loaded to approximately $0.75K_{IC}$. No crack growth was noticed. In addition, two specimens from a standard plate in the T8 condition were placed in the alternate immersion stand in order to investigate the susceptibility to crack corrosion under the most severe environment. The specimens were loaded to approximately $0.9K_{IC}$. The purpose of the experiment was only to force propagation of the crack. No crack growth rates were recorded. Some crack growth was witnessed through the thickness of the specimen but was not visible from the surface. To the knowledge of the dome development project team, there have been no reported K_{ISCC} studies on aluminum lithium 2195 materials.

Discussion and Conclusions

The subscale dome tests showed that the weld and parent material passed Stress Corrosion Cracking testing and survived the Simulated Service cryogenic cycling. The material also exhibited increased cryogenic toughness surviving loading at cryogenic temperatures that was in excess of the proof at ambient temperatures. These data combined with formability spinning and tensile tests enabled the progression of the program from subscale to full Ares I scale. Initial Simulated Service Tests on full scale dome parent material passed cryogenic cycling and displayed a cryogenic toughness superior to the subscale dome. This improvement could be the result of processing parameters or material differences since the plate for the two scales was obtained from different vendors. Future work includes completion of SST and SCC tests on full scale domes, J_{1c} fracture toughness testing, and a full suite of testing on the final full scale dome in the program which is scheduled to be spun in late summer 2010.

Acknowledgements

This work was funded under BAA: NNM05AB11C by the NASA Exploration Development Technology Program.

Material for the manufacturing of the domes was provided by the Ares program

References

1. *ASTM G44 - Practice for Exposure of Metals and Alloys by Alternate Immersion in Neutral 3.5 % Sodium Chloride Solution.* West Conshohocken, PA : ASTM International.
2. *ASTM G 39 –Standard Practice for Preparation and Use of Bent-Beam Stress-Corrosion Test Specimens.* West Conshohocken, PA : ASTM International.
3. *ASTM E 1681 - Test Method for Determining Threshold Stress Intensity Factor for Environment-Assisted Cracking of Metallic Materials.* West Conshohocken, PA : ASTM International, 2003.
4. Brewster, J., Curreri, P. Hoffman, E., Lollar, L. Bank, J., Domack, M., Stewart, T. Edahl, R., Pham, D., Torres, P., Li, T., Shenoy, R., Caratus, A., Reinmuller, R., Russell, C., Cooks, R., Schneider, and J. Tayon, W., *Friction Stir Welded Spun Form Dome Development Project: Sub-scale Spun Formed Dome Report*, NASA BAA: NNM05AB11C, Contract Report, 27 October 2009,



Simulated Service and Stress Corrosion Cracking Testing for Friction Stir Welded Spun Formed Domes



Thomas Stewart*

Andrei Caratus*

Pablo Torres**

Peter Curreri**

*Jacobs ESTS Group

**NASA Marshall Space Flight Center

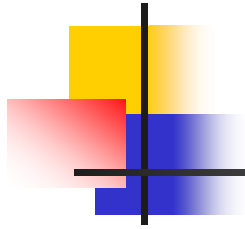
JACOBS
ESTS Group



Simulated Service Test (SST) Strategy



- Based on SST for plate material
- Material tested from subscale and full scale dome (appx 0.1 to 0.2 inches thick)
- One specimen used for fracture data
- One specimen used for SST



Induced Flaws



- All specimens contained induced flaws produced by a two-step method
 - EDM-induced semi-elliptical flaw
 - Followed by cyclic loading in tension to induce a fatigue pre-crack



Fracture Test at Room Temperature

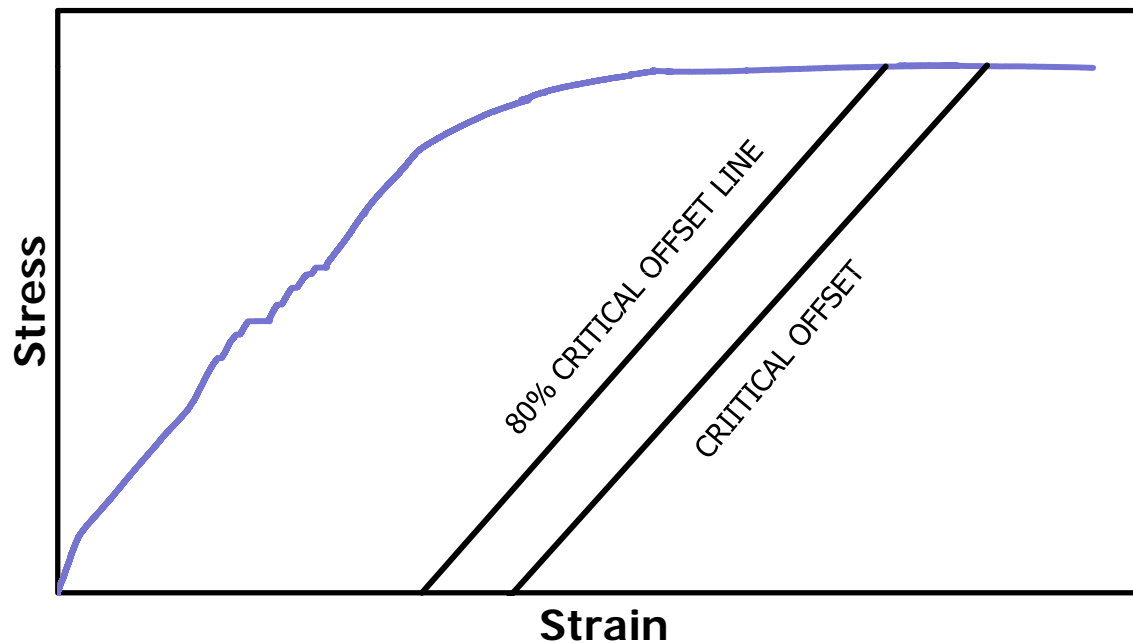


- Performed by monotonic loading until fracture
- Specimen equipped with an extensometer to obtain strain data

Example Fracture Test at Room Temperature



Subscale Specimen Room Temperature Fracture Test





Proof Test at Room Temperature

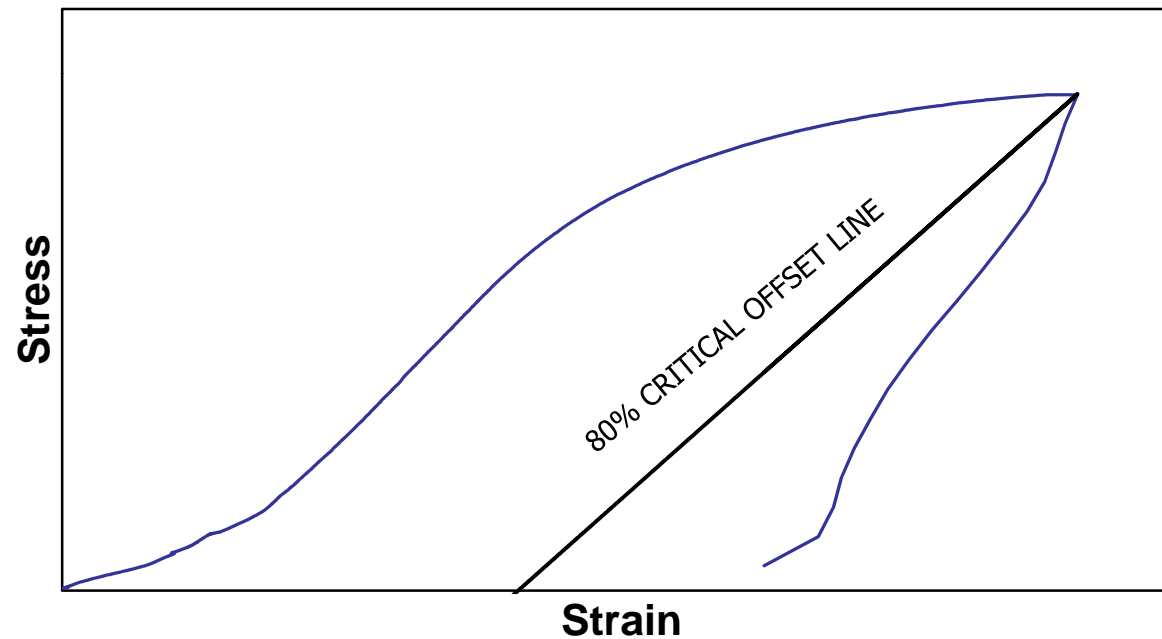


- Performed by monotonic loading until 80% of fracture test critical strain offset was reached
- Specimen equipped with an extensometer to obtain strain data

Example Proof Test at Room Temperature



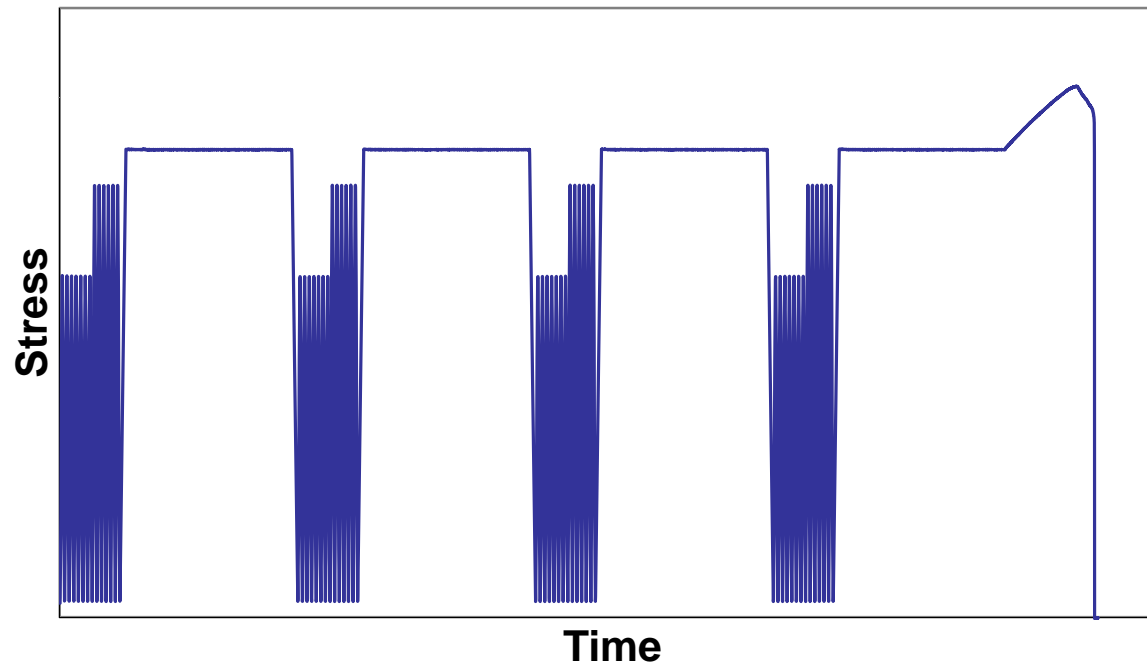
Subscale Specimen Room Temperature Proof Test



Example SST Spectrum in LN2 (-320°F)



Subscale Specimen Cryogenic Cycling Plot





Subscale Dome SST Results



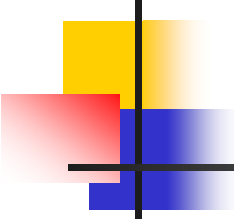
- All specimens fell below the net section stress requirement during fracture or proof
- All specimens survived required post-proof simulated service testing in LN2 (-320F)



Full Scale Dome SST Results



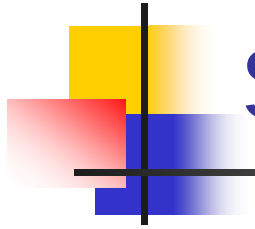
- One fracture and SST test was performed
- The specimens met the net section stress requirement during fracture and proof
- The specimen survived required post-proof simulated service testing in LN2 (-320F)



Subscale Dome Stress Corrosion Cracking (SCC) Testing



- Alternate immersion exposure
- NaCl solution
- Double beam and 4-point bend method used for loading
- Specimens tested at various percentages of yield strength



Subscale SCC Results



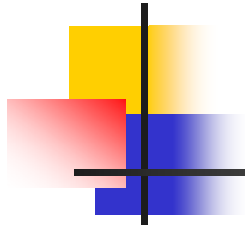
- No specimen failures
- General pitting was observed, which is typical for 2XXX series aluminum alloys
- Results indicate that the material is not susceptible to SCC



Subscale Threshold Stress Intensity Factor for SCC (K_{1SCC})



- Material tested from subscale dome manufactured by different vendor as previously mentioned tests (appx 1.6 inches thick)
- Specimens loaded to $0.75K_{1C}$ in a NaCl solution spray
- Specimens tested from each dome zone (pole, membrane, equator)



Subscale K_{1SCC} Results



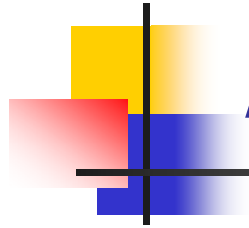
- No crack propagation was witnessed after exposure
- To investigate the most severe loading and environment, specimens were tested at $0.9K_{1C}$ in alternate immersion
 - No data were recorded because the test was to determine the possibility of crack propagation
 - Crack growth was witnessed through the thickness but not at the surfaces



Conclusion



- Subscale SST and SCC testing along with formability and tensile testing provided confidence to move forward to full scale dome fabrication
- Initial full scale SST results display increased strength and cryogenic toughness



Acknowledgements



- Funded by NASA Exploration Development Technology Program (BAA:NNM05AB11C)
- Material for dome fabrication provided by Ares program